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    LCD versus CRT displays: Visual search for colored symbols

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LCD VERSUS CRT DISPLAYS:
VISUAL SEARCH FOR COLORED SYMBOLS

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We examined visual search performance using 52-cm liquid-crystal (LCD) and cathode-ray tube (CRT) displays. Twenty-four participants searched for color-coded navy tactical display symbols using LCD and CRT displays viewed on and off-axis (60 degrees of azimuth). Observers' sensitivity was lower when searching for red and blue symbols (vs. white) viewed off-axis on the LCD, with no comparable problem for off-axis CRT. Colored symbols viewed off-axis on the LCD also produced longer response times in feature search and lower search efficiency in conjunction search. Color coding improved search efficiency overall, relative to an earlier experiment with monochrome (white) symbols (20-80 vs. 200 ms per item). The results argue against the use of current LCD technology for off-axis viewing when color coding is used, but also suggest that LCD and CRT displays are equally effective for on-axis viewing.

INTRODUCTION

This paper describes an experiment comparing the effectiveness of liquid-crystal (LCD) and cathode-ray tube (CRT) displays. In the naval community, there is interest in the use of LCD panels on ships because of their lower power consumption and weight, as well as their lowered susceptibility to electromagnetic interference and smaller footprint. This specific interest mirrors a more general consumer interest in LCD technology for desktop computers.

Studies that have examined human performance with LCDs and CRTs have confounded display technology with other factors, such as display size and pixel resolution (e.g., MacKenzie & Riddersma, 1994; Menozzi et al., 1999; Wright et al., 1999). When resolution of the displays used for existing studies is computed, the display type with higher resolution (in at least one dimension) produced better performance. To properly understand if display type affects performance, display resolution should be constant across display types.

Viewing angle is an important factor in operational display performance. Although reduced luminance and color distortion occur with an LCD viewed off axis (Selhuber and Parker, 1997), it is not known whether these problems in display optics are severe enough to actually affect human performance. The question is important because LCDs have many advantages (as noted above); those faced with the decision about whether to purchase them may be interested in knowing if optical limitations of LCD technology impair an observer's ability to use the display.

Searching for Symbols

Visual search (Treisman and Gelade, 1980; Wolfe, 1994) is a necessary component task for many naval shipboard operations (Nugent, Keating, and Campbell, 1995). In visual search an observer looks for a particular target symbol among multiple distractors, and indicates if the target is present or not. Set size (number of symbols in the display) is varied to assess processing efficiency and accuracy and response time are measured.

Naval tactical displays typically depict a theater of operations with symbols (most commonly representing vessels and aircraft) superimposed on a map background. NTDS (Navy Tactical Display) symbols are currently used for tactical displays on US and Canadian naval vessels. Figure 1 shows 9 NTDS symbols. The shape of the symbol codes its identity (friend-circle, hostile-diamond, unknown-square), whereas contact information is provided by the symbol's orientation (a full symbol indicates surface, pointing up indicates air, and pointing down indicates subsurface).

Hollands, McFadden, Cassidy, and Boothby (2000) examined visual search for the 9 NTDS symbols shown in Figure 1. The symbols were displayed on 52-cm (21") LCD and CRT displays viewed on- and 60 degrees off-axis (azimuth). It was hypothesized that search performance (as measured by response time, and the signal detection sensitivity measure d'; Macmillan & Creelman, 1991) should deteriorate off-axis, especially for the LCD. However, the results showed that although sensitivity decreased with set size, display type and viewing angle had no effect. There was no response time difference between LCDs and CRTs, viewed on- or off-axis. The search rate (slope of the target absent function) was highly inefficient at about 200 ms per symbol (As a point of reference, search rates of 20-30 ms per item are considered inefficient in the visual search literature, Wolfe, 1994).

Figure 1. Set of 9 NTDS symbols used in experiment.

between/within design was used, with the first two factors manipulated between subjects. The two viewing angles were 0 and 60 degrees of azimuth. The three set sizes were 10, 30, and 50.

Each of the 3 x 2 = 6 conditions defined by the combination of Target Color and Search Type was defined as a block of trials. The order of the 6 blocks was counterbalanced using a Latin square. The order of trials within a block was randomized. For each level of Set Size, each of the 3 NTDS symbols for a given target color was shown as a target 3 times, producing 9 *target-present* trials. On the other 9 *target-absent* trials, no target was shown. In the feature search condition, the distractor symbols were sampled with replacement from the set of 6 symbols that did not share its color. In the conjunction search condition, the distractor symbols were sampled from the set of 9 symbols minus the target symbol.

Procedure

Each participant was randomly assigned to a participant number which determined experimental conditions. After participants filled out the consent form, they were screened for color vision using HRR pseudoisochromatic plates in daylight. Participants filled out a consent form, and then read a set of instructions. Then they performed 6 practice trials followed by the experimental trials.

On each trial, the target symbol was shown, the participant pressed a key, and the symbol set was displayed. This display was shown until the participant responded "present" or "absent", whereupon the next trial commenced. Participants responded using the index and middle fingers of their dominant hand to press "present" and "absent" keys (the '1' and '2' keys on the numeric keypad). The participant's response and response time were recorded. It took approximately 75 minutes to run a participant through the procedure. After completion, the participant received a written debriefing form, filled out a questionnaire and discussed the experiment with the experimenter.
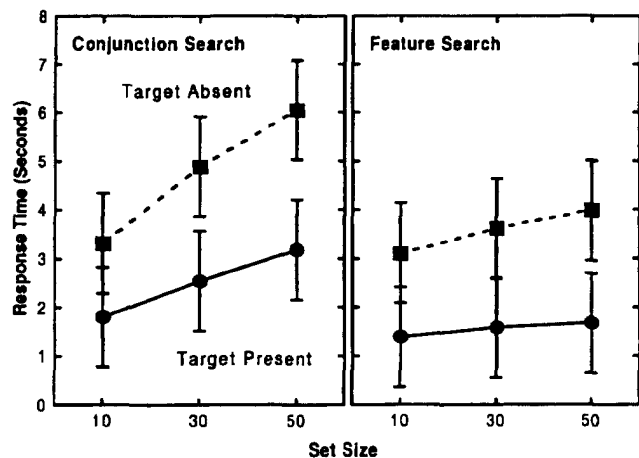

Figure 2. Response time as a function of display type, viewing angle, and color. Error bars indicate the standard error of the mean in all graphs.

RESULTS

Search Type

A mean response time was computed for each participant for each experimental condition. A logarithmic transformation was applied to the data in order to correct for observed heterogeneity of variance. These means were submitted to a between/within analysis of variance (ANOVA) with two between factors (Display Type and Viewing Angle) and four within factors (Target Color, Search Type, Set Size, and Target Presence). An interaction between Search Type, Set Size, and Target Presence was found, and the means are depicted in Figure 2. Response times were longer and increased more with set size in conjunction search than feature search, $F(2,40) = 3.29$, $MSe = 0.014$, $p < .05$ (Figure 2). The search rate (slope of target absent function) was greater for conjunction search than feature search (83 vs. 23 ms per symbol, respectively), $t(23) = 11.95$, $p < .0001$. Feature and conjunction searches are therefore treated separately below.

Feature Search

Sensitivity. A mean sensitivity score (d') was computed for each condition and participant. These scores were submitted to a between/within analysis of variance (ANOVA). Participants showed greater sensitivity for white targets than red or blue targets with the off-axis LCD, but target color had no effect for on-axis LCD or for either viewing angle with the CRT, as shown in Figure 3, $F(2,40) = 14.93$, $MSe = 0.089$, $p < .0001$.

Response time. A mean log response time score was computed for each participant for each feature search condition. These scores were submitted to a between/within ANOVA. For the LCD red and blue symbols ($M = 2.78$ and 2.67 s, respectively) required more time than white symbols ($M = 1.73$ s), but for the CRT target color had no effect ($M = 1.69$, 1.81, and 1.68 s for red, blue, and white, respectively), $F(2,40) = 20.31$, $MSe = 0.020$, $p < .0001$. Red and blue symbols viewed off axis required more time than when viewed on axis, ($M = 2.55$ and 2.61 s vs. 1.83 and 1.86 s for red and blue respectively), whereas viewing angle had little effect for white symbols ($M = 1.74$ s off vs. 1.67 s on), $F(2,40) = 10.15$, $MSe = 0.020$, $p < .0005$.

Each participant's target-present response times were regressed over set size for each target color. Regression slope values were submitted to a between/within ANOVA. Blue and red symbols viewed off-axis on the LCD produced greater RT slopes than white symbols, but target color had no effect on slopes with the LCD viewed on axis, or with the CRT from either viewing angle, $F(2,40) = 5.07$, $MSe = 78.61$, $p < .05$. Mean values are shown in Figure 4. In other words, off-axis viewing made search for colored symbols less efficient for the LCD, but had a negligible effect on search efficiency for the CRT.

Thus, the problem for LCD manufacturers is to improve the display technology to afford better off-axis viewing of colored symbols. In particular, given our photometric measurements, the problem appears to be the reduced luminance of LCD pixels viewed off axis. Techniques that increase the off-axis luminance emitted from a pixel have recently been developed (e.g., NEC XtraView). Such techniques may help address the off-axis problem observed in this study.

Search rates in this experiment (23 and 83 ms/item for feature and conjunction search, respectively) were faster (i.e., more efficient) than those obtained by Hollands et al. (2000) (200 ms/item). Thus, the slow inefficient search rates for NTDS symbology obtained by Hollands et al. (2000) improved with the addition of color. In combination, these results confirm that the recent practice of color coding NTDS symbology improves search efficiency.

Any study comparing different display technologies is to some degree limited to the particular technology tested. The panel used in this study was state-of-the-art technology at the time the study was conducted. However, given rapid advances in display technology, the results cannot be interpreted as a general criticism of LCDs, but rather serve to highlight specific problems with existing technology that can be addressed by technological innovation.

Design Implications

The results have the following implications for display design. First, CRT display technology is encouraged for shared or collaborative situations where off-axis viewing is likely, especially when color coding is used. Second, the development of LCD technology that addresses off-axis viewing with a larger viewing cone is encouraged. Third, the use of redundant color coding with shape is recommended in situations where an observer searches for an iconic symbol on a CRT display or on-axis with an LCD.

ACKNOWLEDGMENTS

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